

Undersea Communication Network Self-Localization during the Unet'08 Seatrial

Doug J. Grimmett
SPAWAR Systems Center Pacific
53560 Hull Street
San Diego, CA 92152-5000 USA

Abstract- The U.S. Navy Seaweb project has been advancing the state-of-the-art in undersea acoustic networks over the past decade. Seaweb utilizes commercially available telesonar modems and has developed link/network layer firmware to provide a robust undersea communications capability. Gateway technologies and a Seaweb server have been successfully developed. Over 50 successful deployments of Seaweb networks have been made, most focusing on engineering development of the system, while others were interfaced to various Navy applications for demonstration. Recent progress has been made in enhancing the autonomy of these undersea communications networks. Seaweb networks now have the capability to perform self-discovery and establish the connectivity of the network autonomously. A byproduct of the self-discovery process is the set of inter-nodal range measurements for nodes that have communication connectivity. With this information, a centralized control node may estimate the localization of the network layout, subject to some constraints. This paper provides an overview of the Seaweb undersea networking capability and describes the localization algorithm. Its limitations and constraints are also discussed. The algorithm is applied to actual experimental data collected by a Seaweb network deployed during the Unet'08 sea trial. Results are shown for two network topologies deployed during that trial.

I. INTRODUCTION

Through-water acoustic communications have potential to extend wireless networking capabilities from the terrestrial to the undersea domain. Fig. 1 depicts a realization of the undersea FORCEnet concept, with an effective integration of warriors, sensors, command/control, networks, platforms, and weapons, from undersea to space to land.

The U.S. Navy Seaweb project [1-2] has been advancing the state of the art in undersea wireless acoustic communication networks over the past several years. Low-throughput data rates, short ranges, and long message delivery latencies are characteristic of undersea acoustic communications. These physical-layer constraints greatly impact point-to-point communications, and challenge efforts to create wireless multi-node networks under the sea. Nonetheless, steady progress has been made in fielding successful wireless undersea acoustic communication networks.

The latest generation modem now available significantly increases Seaweb communication capabilities, including increased computing power, memory, and storage. This

upgrade allows Seaweb to be operated with more autonomy, self-intelligence, and adaptivity, as an ad-hoc network. Future Seaweb networks will self-adapt to provide optimal operations in dynamic environmental and operational conditions. Variable power and signaling schemes, together with dynamic routing methods are expected to provide increased communication capabilities for a number of Navy applications. This paper describes an automated method for the network to physically localize the nodes contained within it. Node localization is important in understanding network performance, enabling communications with mobile nodes or other sensors, and retrieval of the network.

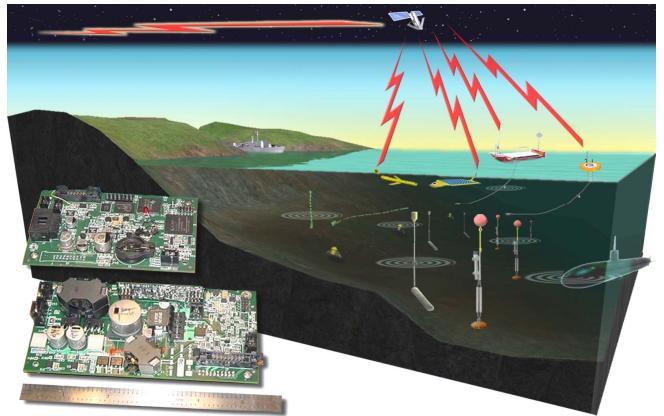


Figure 1. (U) Seaweb technology enables communications within the undersea domain and connectivity to terrestrial networks.

Progress has been made for Seaweb networks to self-discover, and self-organize after deployment [3]. A seed node begins a process which interrogates for possible neighbor nodes within communications range. The process continues until the communication network's inter-nodal connectivity is completely determined. Once this is done, communication message routing paths can be automatically established. A by-product of this network self-organization process is the set of inter-nodal ranges. These data are obtained when a transmitting node pings and receives a delayed response from another node. The timing of the reply provides a way to determine the inter-nodal range. Provided that there is

sufficient connectivity between the nodes of the network, the set of inter-nodal ranges can be used to solve for the relative locations of the nodes, using a cross-fixing equation and other geometric relationships. When a sufficient number of “anchor” nodes exist (those with absolutely known positions, as for a gateway node equipped with GPS), the network’s nodes may be localized absolutely.

This paper proceeds as follows. The Seaweb undersea network is first described in section II. Section III describes the localization cross-fixing formulas and algorithm, and explains constraints which may prevent a complete solution of the network. In section IV, the method is applied to actual experimental data collected by a Seaweb network deployed during the Unet’08 sea trial.

II. SEAWEB NETWORK DESCRIPTION

The Seaweb system consists of various components, which are now described in more detail.

A. Telesonar modems

Seaweb utilizes commercially available telesonar modems [4]. Seaweb modem technology is currently available in a 4th generation model, which has increased processing, memory, and battery efficiency over previous versions. This upgrade allows Seaweb to be operated with more autonomy, self-intelligence, and adaptivity, as an ad-hoc network. Fig. 2 shows a single telesonar modem in a typical deployment configuration with mooring weight, acoustic release and subsurface float. The configuration can be easily deployed by hand from small or large boats.

Multiple modems can be deployed into a network with a topology to suit the particular communications objective [5]. Modems can act as “repeater/relay” nodes, or they may be interfaced directly to sensors, vehicles, and gateway buoys. Information is digitally encoded using modulation schemes such as Multiple Frequency Shift Key (MFSK) with information bit-rates ranging from 140 to 2400 bits/sec. Rates of 800 bits/sec have been reliably used in most of the shallow water environments where Seaweb has been deployed.

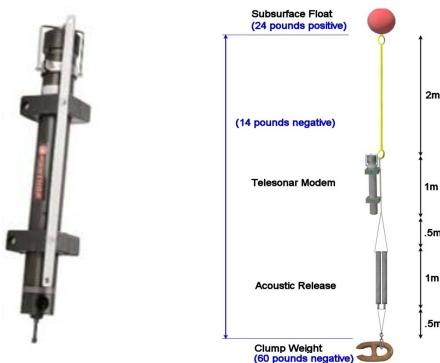


Figure 2. Telesonar modem package (left); single Seaweb node deployment configuration (right).

B. Seaweb networking firmware

Government proprietary link-layer and network-layer firmware has been developed for use with the commercial modems. This firmware extends the modems’ functionality from operating as point-to-point links to operating as an organized and robust network. At the heart of this firmware is the implementation of various link and network control frames, which implement communications protocols based on Multiple Access Collision Avoidance (MACA) suitable for underwater networks [6]. Control frames are short 9-byte utility packets which are transmitted between modems for reliable and effective control/operation of the network. The following specialized control frames have been successfully implemented into Seaweb networks.

- *RTS* – Request-to-Send. Transmitting node request to access the channel to send data to a specific receiver node.
- *CTS* – Clear-to-Send. Receiver node permission for transmitting node to send data.
- *HDR* – Header for subsequent data packet or sub-packets.
- *SRQ* – Selective Automatic Repeat Request. A form of error correction where the receiver node responds to the transmitter to resend specific missing or corrupted data sub-packets.
- *ACK* – Acknowledgement from receiver node to transmitter node that transmitted data was successfully received.
- *PING* – Connectivity and ranging query from a transmitting node to one or more other nodes.
- *ECHO* – Response from receiving node to a transmitting node’s PING command, including inter-nodal range information.
- *RCPT* – Response from destination node to source node (through intermediary nodes along a route) that network message was received.

The *PING* and *ECHO* control frames provide the ranging information needed for network localization.

Fig. 3 depicts an example of a typical communications dialog of control frames between modems which facilitate the exchange of data. Because of the importance of control frames in managing the network’s operation, they are transmitted with slower bit rate than data packets (typically 140 bits/sec vs. 800 bits/sec) for communications reliability.

C. Gateway technologies

Gateway technology allows the undersea acoustic communications network to be connected to terrestrial communications networks via radio or satellite. Fig. 4 shows a Radio-communications (Racom) gateway buoy used in Seaweb networks. A telesonar modem interfaces to radio and satellite connections. Gateway buoys are typically moored, and are powered by batteries and solar panels. Using this technology, undersea messages may be converted to TCP/IP messages, and visa versa.

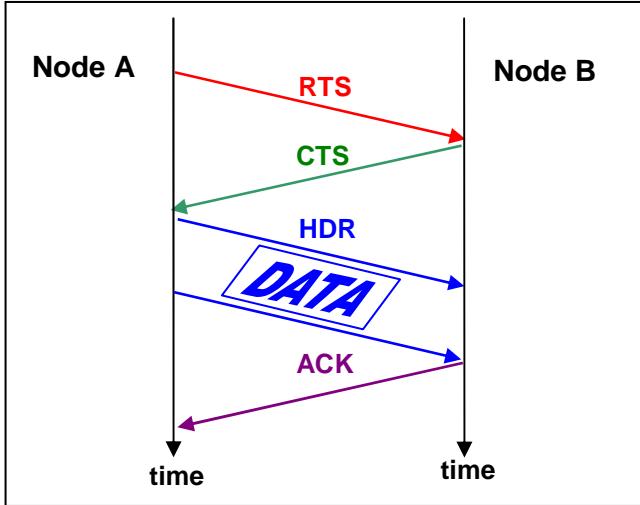


Figure 3. Depiction of Seaweb communications exchange between nodes A and B, using control frames.



Figure 4. A moored Seaweb Racom gateway buoy.

D. Network server

A Seaweb server has been developed which provides an operator interface to the undersea network via a gateway node [7]. The server is a suite of software that operates at manned command centers ashore, afloat, submerged, or aloft. It provides access to operations of the network via a web browser. Incoming and outgoing data and network control messages may be archived into a database. The Seaweb server provides an effective means of managing, controlling, and reconfiguring (if necessary) the undersea network, and for distributing data to client subscribers.

III. SEAWEB NETWORK SELF-LOCALIZATION

Seaweb undersea communication networks are advancing in capability due to the emergence of the latest generation of acoustic modem, which has vastly increased processing capability and storage capacity. This has enabled the implementation of ad hoc networking capabilities such as

network self-discovery [3] and automatic establishment of routing paths. A seed node begins a process which interrogates for possible neighbor nodes within communications range. The discovered nodes repeat the process until the communication network's inter-nodal connectivity is completely determined. Once this is done, communication message routing paths can be automatically established, according to different criteria and the communications objectives [8]. A by-product of this network self-organization process is the set of inter-nodal ranges. These data are obtained when a transmitting modem pings and receives a delayed response from another node. The timing of the reply provides a way to determine the inter-nodal range. An approach to determining the localization is described in [9]. Here we describe a network self-localization algorithm along with an initialization method and the localization constraints.

A. Localization constraints

The communications connectivity of the network will depend on its physical topology, and the acoustic conditions in the local environment. In most cases it is assumed that there will not be full connectivity in the network, i.e., that there will be nodes which are unable to communicate with other nodes. This may impact and constrain the ability to fully localize the communication network. It also makes it difficult to implement a simultaneous, global solution (eg. via Multidimensional Scaling (MDS), etc.). Here we investigate an iterative approach which successively localizes nodes and assimilates them into a network map one at a time.

Network localization may be accomplished at two different levels: “relative” solutions and “absolute” solutions. A solution of nodal locations relative to other nodes in the network may be obtained, even when there are no nodes in the network with absolute, known (eg. GPS-derived) locations. When there are a sufficient number of nodes with absolute location information (termed “anchor nodes”), an absolute localization solution may be obtained. Fig. 5 shows a depiction of these cases. In Fig. 5a, three different (of an infinite number of) possible placements of the network’s relative solution are shown, in the case that only a single anchor node is available. As can be seen, the relative solution can be rotated around the anchor node as well as flipped (in the plane of the solution space). If two anchor nodes are available, as shown in Fig. 5b, there are two possible absolute localization solutions, flipped in the plane about the line connecting the anchor nodes. If three (or more) anchor nodes are available, a single absolute localization solution can be obtained for the network, as shown in Fig. 5c.

We now consider the constraints on localizing a particular node within a network (applicable to both “relative” and “absolute” solutions). A subsequent section will provide the localization equations. To determine an unambiguous relative location of a node, internodal ranges from at least three other nodes (with known absolute or relative positions) must be available. This constraint is depicted in Fig. 6. When only a

single internodal range is available, there are an infinite number of possible solutions (lying upon the circle around the known node), for the localization, as seen in Fig. 6a. Fig. 6b shows the case when two internodal ranges (from nodes with known relative locations) are available, resulting in two ambiguous solutions, where the two ranging circles intersect. When three (or more) internodal ranges are available, a single unambiguous location is obtained, as shown by the single cross-fixed location in Fig. 6c. If there are more than three internodal ranges available, there is redundant information and the solution is over-determined. Sometimes this may lead to an improved localization estimate, but in other cases it has been shown to degrade estimates when one (or more) of the redundant measurements has large errors [10]. The algorithm presented here chooses which set of three internodal measurements is most suitable for obtaining a localization solution.

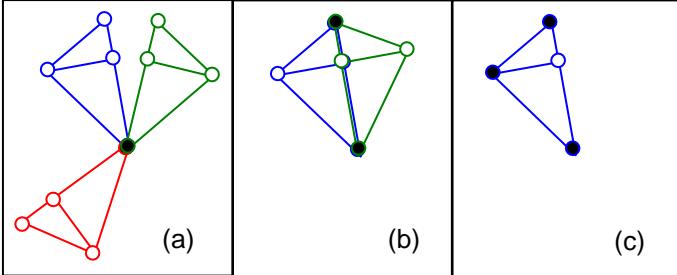


Figure 5. Possible absolute localization solutions for a single, relative network localization solution, as a function of the number of anchor nodes (indicated by black dots); (a) Single anchor node, (b) Two anchor nodes, (c) Three anchor nodes.

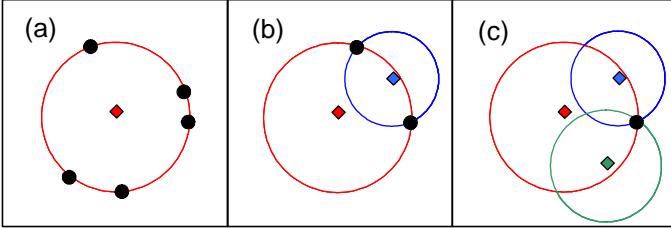


Figure 6. Possible relative localization solutions (indicated by black dots) for a single node with internodal ranges from other nodes with known relative locations; (a) One node (red), (b) Two nodes (red and blue), (c) Three nodes (red, blue, and green)

B. Localization algorithm initialization

After the self-discovery process has finished, a internodal range matrix is constructed (square matrix with size equal to the number of nodes). If multiple (eg. bidirectional) measurements are available between a single pair of nodes, they are averaged. Some error checking is done to remove anomalous measurements. Missing measurements are left blank. Other network analysis is done to determine:

- For each node, a list of connected nodes
- List of all connected triangles
- List of all edges in triangles
- List of all nodes not uniquely localizable

The localization algorithm is initialized by considering the master node. The master node is the primary, initial node used in the Seaweb self-discovery process. It is usually also a Gateway node. Ideally, the master node is also an anchor node, which has a known, absolute position. It is used because it is guaranteed to (directly or indirectly) connect to all other discovered nodes. First we evaluate if the “master” node is a part of a “seed” triangle. A seed triangle is a set of three nodes for which all (three) internodal range measurements are available. These three nodes will form a “seed” triangle for the algorithm’s initiation. If the master node is part of more than one potential seed triangle, the nodes forming the triangle which is most close to equilateral is selected. The most equilateral triangle is selected because it provides the most distributed set of starting nodes, which will minimize the potential for subsequent inaccuracies due to the Geometric Dilution of Precision (GDOP) effect¹ [10].

Fig. 7 shows the geometry of a seed triangle. We assume the master node is a part of this triangle and it is placed into a relative coordinate system at (0,0). Given that we have the lengths of the triangle’s sides, we can use the side-side-side (SSS) formula to solve for the interior angles, as

$$\begin{aligned}\theta_A &= \cos^{-1}\left(\frac{r_B^2 + r_C^2 - r_A^2}{2r_B r_C}\right) \\ \theta_B &= \cos^{-1}\left(\frac{r_A^2 + r_C^2 - r_B^2}{2r_A r_C}\right) \\ \theta_C &= \cos^{-1}\left(\frac{r_A^2 + r_B^2 - r_C^2}{2r_A r_B}\right)\end{aligned}\quad (1)$$

where r_A , r_B , and r_C are the ranges between the nodes. We then rotate the solution so that one edge is situated along the $+x$ axis. Using these angles and ranges, we calculate the relative x-y coordinates of the seed triangle. From this seed triangle an iterative process for determining the locations of other nodes is commenced, as described subsequently.

C. Node localization algorithm

Fig. 8 illustrates the localization of a node relative to three other nodes with known location. The three nodes provide three range measurements, which defines circles given by

$$r_i^2 = (x - x_i)^2 + (y - y_i)^2. \quad (2)$$

Taking three of these measurements, we obtain a system of three equations with two unknowns, but it is non-linear. Using the method described in [10,11], differences of the equations can be taken, which results in a system of two equations with

¹ The GDOP effect worsens when the nodes used for cross-fixing are located at similar angles relative to the unknown node’s location.

two unknowns. This provides the advantage that it becomes a linear system. The resulting localization equation for range data from three nodes is shown [10] to be:

$$Z_k = \begin{bmatrix} x \\ y \end{bmatrix} = \frac{1}{2} P^{-1} \underline{a} \quad (3)$$

where

$$P = \begin{bmatrix} (x_2 - x_1) & (y_2 - y_1) \\ (x_3 - x_2) & (y_3 - y_2) \end{bmatrix} \quad (4)$$

$$\underline{a} = \begin{bmatrix} (r_1^2 - r_2^2) + (x_2^2 - x_1^2) + (y_2^2 - y_1^2) \\ (r_2^2 - r_3^2) + (x_3^2 - x_2^2) + (y_3^2 - y_2^2) \end{bmatrix}. \quad (5)$$

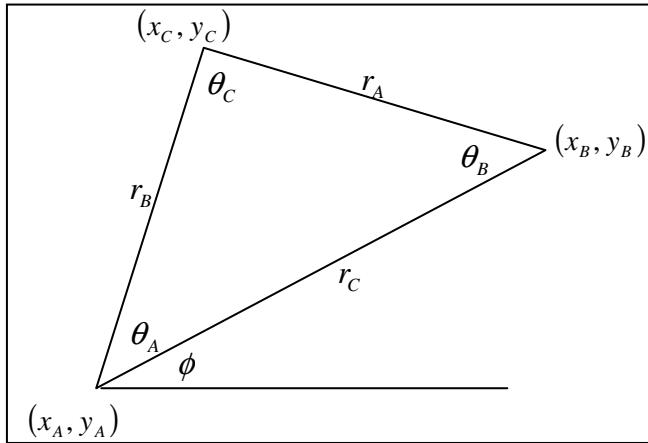


Figure 7. Telesonar modem package (left); single Seaweb node deployment configuration (right).

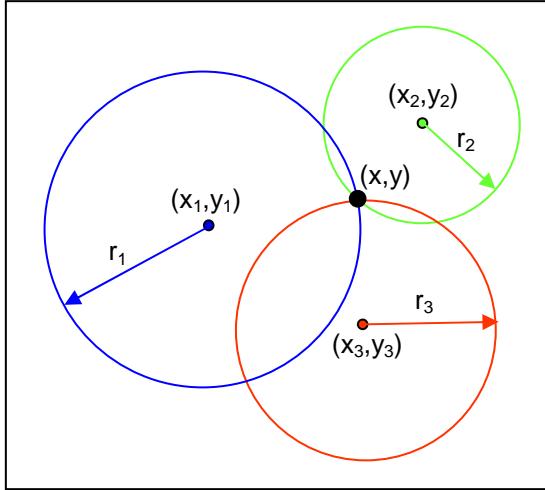


Figure 8. Telesonar modem package (left); single Seaweb node deployment configuration (right).

If range data is available from only two nodes, then an alternate quadratic form of the localization equation can be formed, which results in two ambiguous solutions [12]. A

reasonable guess of which of the two solutions is correct can be made by choosing the one which is furthest away from the nodes with which it is not connected. The underlying assumption here is that increased internodal range decreases the probability of connectivity. This has been implemented in the localization algorithm, however, these localizations are not performed until all of the cross-fixes from three nodes are determined.

The algorithm starts with a seed triangle and finds all nodes which are connected to the nodal vertices of the triangle to localize. If there is more than one node, they are taken in sequence, in order of decreasing GDOP potential. Once all possible localizations are made with the seed triangle, additional localized triangles within the network are considered using the same process. This continues iteratively until all connected nodes (with two or more connections) have been localized.

IV. APPLICATION TO UNET'06 SEATRIAL DATA

Unet'08 was a seatrial conducted under the Technical Cooperation Program (TTCP), a multinational collaboration between the nations of Australia, Canada, New Zealand, U.K., and the U.S. The objective of the Unet working group is to address issues related to undersea communications and networking. The seatrial was conducted in St. Margaret's Bay, Nova Scotia, in June of 2008, and included the support of several research vessels.

During the trial, Seaweb communications networks were deployed, and experiments conducted with various physical topologies. Network self-discovery was performed and internodal range tables obtained for two network configurations. The true deployment positions for the network's modems were recorded by handheld GPS upon deployment. This provides ground truth for comparisons with the automatic localization results. For this analysis, we assumed there was only one anchor node, which was the location of the Seaweb gateway node which initiated network self-discovery processes. As such, the localization algorithm was able to produce relative, not absolute network localization solutions. The obtained relative localization solutions were then rotated and/or flipped in order to obtain a "best fit" with the absolute, known ground truth.

A. Case 1, 8-node network

Eight nodes were deployed in the area, with the internodal ranges as shown in Table I. The first row and column show the node number, the second row and column show the node name, and the rest of the cells show the internodal ranges obtained by the system. Note that "NaN" indicates when data was not obtained. The network connectivity was analyzed and all nodes were found to be a part of a triangle. There were 22 connected triangles, with three triangles that contained the anchor node (#1). There were 20 edges, all of which were part of triangles. Here, a complete, relative solution was possible.

TABLE I
INTERNODAL RANGES FOR CASE 1.

	1	2	3	4	5	6	7	8
	03	20	21	22	23	24	13	15
1	03	NaN	442.3	NaN	NaN	NaN	NaN	5503.3
2	20	443.4	NaN	924.3	1866.2	2810.7	3732.7	7197.1
3	21	NaN	930.4	NaN	949.9	1907.6	2850.4	8124.8
4	22	2312.1	1872.1	949.8	NaN	964.8	1920.8	9051.6
5	23	NaN	2814.5	1905.5	963.3	NaN	964.8	NaN
6	24	NaN	3733.5	2846.8	1916.5	962.1	NaN	NaN
7	13	NaN						
8	15	NaN	NaN	NaN	7749.9	NaN	NaN	1526.8

The localization algorithm was run, using node #1 as the master node. Three seed triangles were found containing the master node. Triangle 1-2-4 was determined to be the most equilateral, and its relative positions were solved. All other nodes were connected to by three or more nodes and their positions were iteratively solved. The resulting relative localization solution was flipped in the analysis plane and rotated by -87° in order to best fit the ground truth for comparison. Fig. 9 shows the localization solution compared to ground truth. There is good agreement between the two. The master node is shown labeled by “03”. Nodes extend to the north along a slight arc, with two nodes located at long range to the south. Fig. 10 shows the accuracy of the result with an overlay of ground truth and the localization method, for the northern nodes. Fig. 11 shows the localization error between the truth and the algorithm’s solutions (with the best fit rotation) for each of the nodes. In this case we see that the localization accuracy is generally better than 100 meters, except in the case of the more distant nodes, where the GDOP effect is more pronounced.

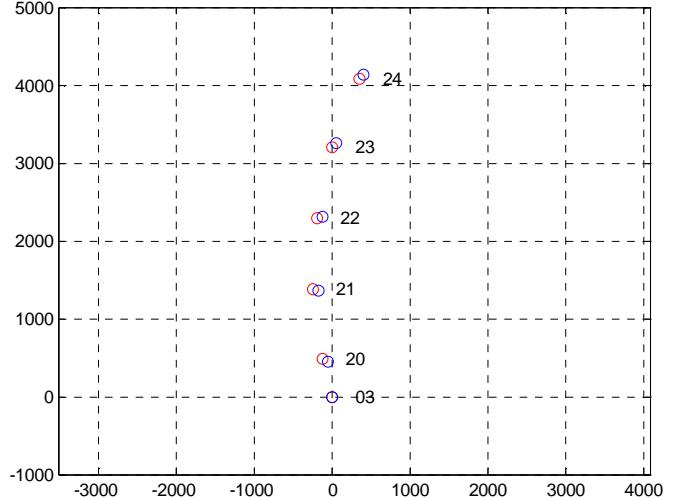


Figure 10. Case 1 Seaweb network topology ground truth (red) and localization estimates (blue). Node “03” is the master node.

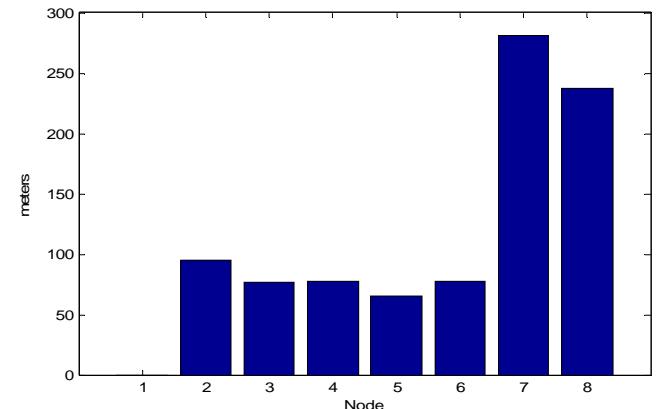


Figure 11. Case 1 localization error, per node.

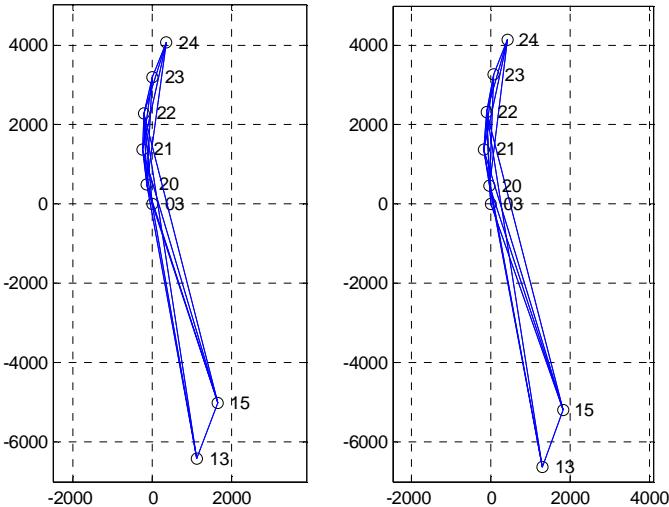


Figure 9. Case 1 Seaweb network topology ground truth (left); Network localization solution, rotated and flipped (right).

B. Case 2, 13-node network

Thirteen nodes were deployed (including six of the same nodes analyzed in case 1) in the northern area. A internodal range table was constructed, and other network analysis performed. In this case, all nodes were found to be a part of a triangle. There were a total of 82 triangles identified, 18 of which included the master/anchor node (“03”). There were 51 edges identified, all within triangles. Therefore, a complete network solution is possible, as there is a large amount of network connectivity and measurement redundancy.

The localization algorithm was run, using node #1 (labeled as “03”) as the master node. The seed triangle with nodes “03”/“22”/“42” was found to be the most equilateral and was used to initiate the localization process. All other nodes were localized (in sequence), using the sets of three with the least potential GDOP. A complete, relative localization was achieved. This solution was then found to fit well to ground truth when flipped and rotated by -85° . Fig. 12 shows the

ground truth locations of the network, compared to the localization algorithm's output. The overlaid positions are shown in Fig. 13, where we see good accuracy in the nodes to the south and increasing errors in the estimation as for nodes situated more to the north. Fig. 14 shows the estimation error per node, with a trend for less accuracy for nodes further away from the master node (nodes numbered 1-6 correspond to nodes labeled "03", "20", "21", "22", "23", "24, respectively; nodes numbered 7-13 correspond to nodes labeled "16", "40", "41", "42", "43", "44", "45", respectively. It is clear that for this iterative method some errors in the estimation of nodes accumulate, worsening subsequent localizations as they are made.

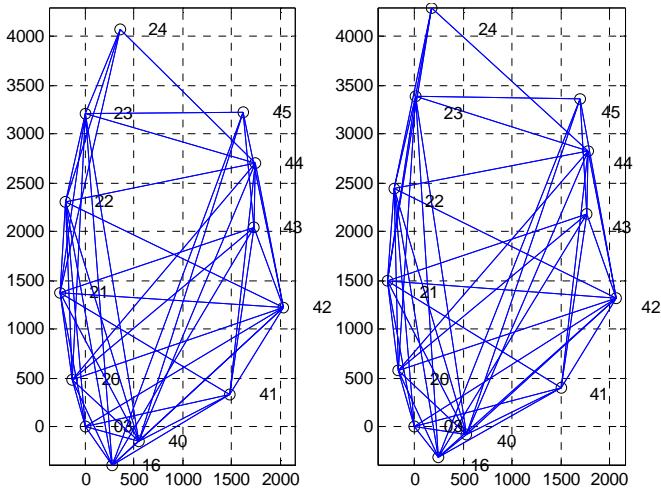


Figure 12. Case 2 Seaweb network topology ground truth (left); Network localization solution, rotated and flipped (right).

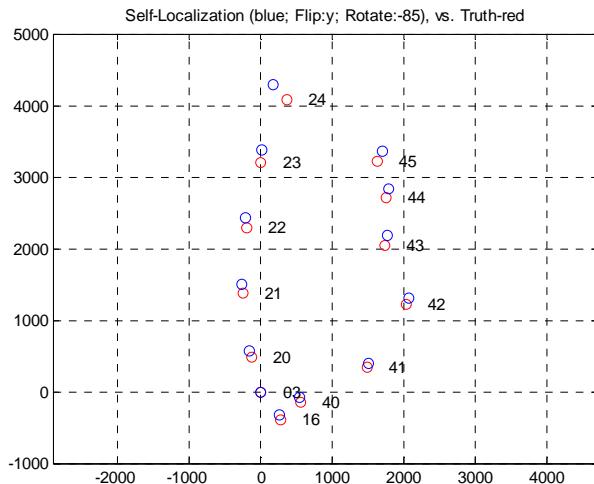


Figure 13. Case 2 Seaweb network topology ground truth (red) and localization estimates (blue). Node "03" is the master node.

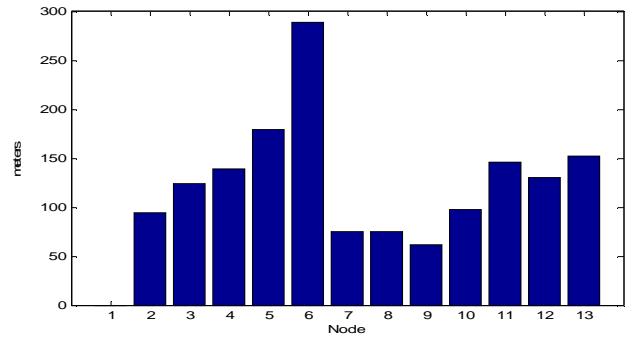


Figure 14. Case 2 localization error, per node.

V. SUMMARY AND CONCLUSIONS

A simple and effective approach for acoustic network localization has been presented. When applied to Seaweb acoustic communication networks deployed in the Unet'08 seatrial, good localization results are obtained. It is observed that the iterative process used here can lead to accumulated errors for nodes which are localized after and which are located further away. Future efforts will attempt to statistically characterize the error uncertainties of the method so that more intelligent sequencing can be made for node assimilation into the network map.

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